MATCHING THE REFRACTIVE INDEX

DENSITY STRATIFIED FLOWS

by

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Introduction

The use of optical methods such as Laser Doppler Velocimetry (LDV) and laser induced fluorescence techniques (LIF) in experimental fluid mechanics is becoming very common. The greatest advantage of such methods is that measurements are made without disturbing the flow. A major impediment to using optical methods to study density stratified flows is the variation of the refractive index within the flow field. McDougall (1979a) has proposed a method for the reduction of refractive index variations while maintining a density difference. The method relies on the fact that various solutes in, say, water can contribute to the density and to the refractive index of the solution in different proportions.

A new pair of solutes (ethanol and NaCl) were found to be suitable for use in LDV and LIF studies of stratified flows. In some circumstances the new pair is more useful than that described by McDougall (1979a).

Practical Considerations

Consider two solutes A and B dissolved in water. The refractive index n and density ρ of a solution of both A and B can be expanded as

$$n = 1.3330 + a_{n1}C_A + a_{n2}C_A^2 + b_{n1}C_B + b_{n2}C_B^2 + c_nC_AC_B + \text{higher order terms} \quad (1)$$

$$\rho = 0.9982 + a_{\rho1}C_A + a_{\rho2}C_A^2 + b_{\rho2}C_B^2 + c_\rho C_AC_B + \text{higher order terms} \quad (2)$$

where C_A in the concentration of component A, C_B is the concentration of component B, and the a's, b's, and c's are constants.

To prepare two solutions (solutions 1 and 2) of the same refractive index ($n_1 = n_2$ where n_i is the refractive index of solution i) but with a prescribed density difference $\Delta\rho$, two considerations have to be kept in mind:

(1) There is an upper limit on $\Delta\rho$ that can be achieved. This is due to non-linear terms in equation (1).

(2) No double diffusive convection (salt fingering) should occur at the interface.

As for the first limitation, it is to be observed that the refractive index, n_{12}, of a mixture of solution 1 and 2 is generally different from n_1. The maximum difference between n_{12} and n_1, denoted by $\max|n_{12}-n_1|$ is an increasing function of $\Delta\rho$ as shown in Figure 1. A certain optical method will break down when $\max|n_{12}-n_1|$ exceeds Δn_{all} (or $\Delta\rho$ exceeds $\Delta\rho_{max}$) where Δn_{all} is the maximum allowable change in the refractive index. It is to be noted here that Δn_{all} is a function of both the distance the beams traverse through an interface and the type of optical application. In general, the longer the beam path, the smaller Δn_{all} for equal performance. Moreover, Δn_{all} for an LDV application is in general different than that for an LIF measurement. It was found experimentally that a value of $\max|n_{12}-n_1| \sim 0.0001$ can affect the quality of LDV measurements when the beams traverse 30 cm of interface.

To avoid double diffusive phenomena a certain relationship has to be satisfied by the solutes. McDougall (1979a) discusses this problem at length and concludes that the relationship is very stringent and excludes most pairs of solutes. In his experiments, McDougall (1979a) used Epsom salt ($MgSO_4$) and sugar as solutes with the sugar solution being less dense.

In this work we propose the use of common salt (NaCl) and ethanol as solutes. By using this pair of solutes double diffusive phenomena are eliminated since both solutes are stably stratified. (An ethanol solution is less dense than pure water).

The use of salt and ethanol has an advantage in applications where the volume of the lower denser layer is large and the upper layer is relatively small. In that case the use of table salt/ethanol instead of Epsom salt/sugar is more economical. Moreover, the use of sugar in the lab can be impractical because it tends to stick to surfaces and supports the growth of microorganisms. However, the use of salt/ethanol has its own disadvantages. First, there is a significant temperature increase when alcohol is added to water. This can be remedied by either adding ice or waiting for the solution to attain its equilibrium temperature. The second is that alcohol is volatile. This can be a handicap when the upper layer is vigorously mixed. One way around this problem is to cover the tank. Even if only 95% of the surface is covered, negligible amounts of alcohol escape within several hours in the presence of mixing.

Experimental Verification:

The application of the method was tested using an LDV system in a tank 1.14 x 1.14 x 3.00 m (l x w x h). Two different solutions were prepared: one containing salt and the other containing ethanol. Approximate amounts of both solutes were added so as to get two solutions with close refractive indices and a density difference of 0.021 g/cm^3. The amounts were determined from tables of refractive indices and density versus mass of solute added as published in Weast (1976). It was found that obtaining two solutions of the same refractive index by relying on published tables alone can be very frustrating. The main reason is the presence of impurities in

both the solutes and the water. A refractometer proved invaluable in determining the difference in the refractive indices of the two solutions. The refractometer used was an American Optical model 10419 that provided readings to within 0.0001. Appropriate amounts of solutes were added to match the indices within the tolerance of the refractometer.

In order to match the refractive indices to within less than the tolerance of the refractometer ethanol solution was injected from a dropper into a rectangular plexiglass box 6 x 6 x 15 cm (l x w x h) that contained salt solution. The resulting plume was observed on a shadow graph. Then, the concentration of the ethanol solution was adjusted very slowly by adding either very small amounts of ethanol or water and the resulting solution was injected into the plexiglass box. This trial and error procedure continued until the plume was not visible on the shadow graph. At that point the ethanol solution was carefully poured over the salt solution in the large tank after ample time was allowed for the ethanol solution to get to its equilibrium temperature.

The upper fluid was disturbed vigorously using manual power. LDV measurements were performed by using laser beams that traversed the tank horizontally through the interface and measurements were made throughout the interfacial layer. Details of the LDV system are described in Papanicolaou (1984). The LDV output signal was continuous and was unaffected by the presence of the interface. Visual observation indicated no significant displacement of the laser beams. Moreover, salt fingers were not observed at the interface.

In the above experiment the density difference was 0.0207 g/cm^3. McDougall (1979b) was able to carry successful LDV measurement with a density difference between the layers of about 0.015 g/cm^3 using a tank

of dimensions 25.4 x 25.4 x 46.0 cm (l x w x h). The maximum distance the laser beams had to traverse through the interface in McDougall's experiments was 25.4 cm as compared to 114 cm in our experiment. It is expected that by using the NaCl/ethanol solute pair in tanks comparable in size to McDougall's (1979b), LDV measurements can be done successfully with density differences of about 0.03 g/cm^3. This value is comparable to the maximum density difference across an interface in a stratified natural body of water.

References

1. McDougall, T.J. (1979a); J. Flud Mech. 93 part 1, pp. 83-96.

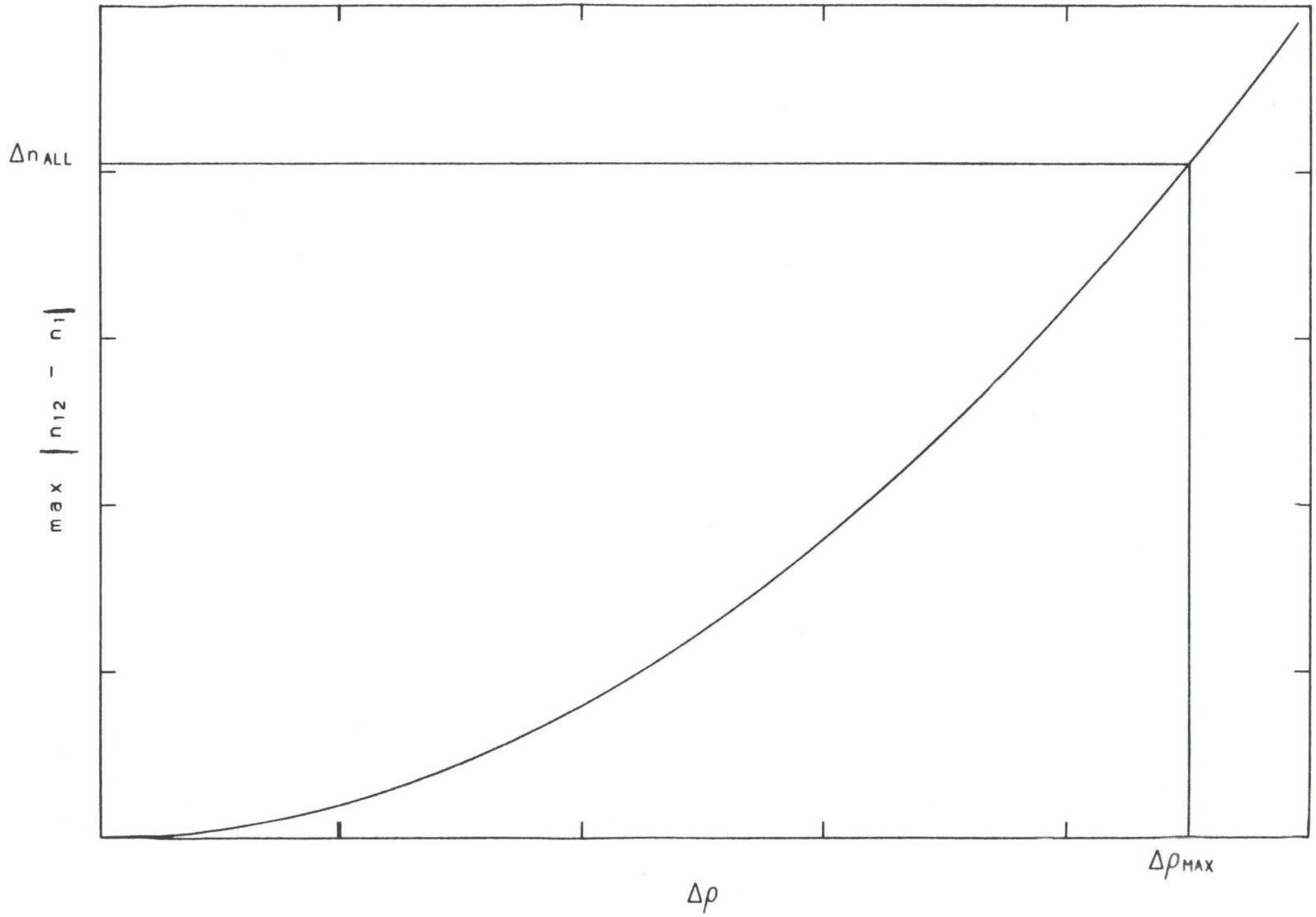
2. Weast, R.C. (1976); Handbook of Chemistry and Physics. 56th ed., C.R.C. Press.

3. Papanicolaou, P. (1984); Mass and momentum transport in turbulent buoyant vertical axisymmetric jets. Ph.D. thesis, California Institute of Technology.

4. McDougall, T.J. (1979b); J. Fluid Mech. 94 part 3, pp. 409-431.

Figures

Figure 1 Typical variation of $\max|n_{12}-n_1|$ versus $\Delta\rho$. $\Delta\rho_{max}$ is the value of $\Delta\rho$ corresponding to Δn_{all}.


Δn_{ALL}
max $|n_{12} - n_1|$
$\Delta\rho_{MAX}$
$\Delta\rho$